LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the twentieth of the preceding month; for the second issue, the fifth of the month. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

The Nuclear Spin of Deuterium

The relative intensities of 29 lines have been measured in the α-bands of the molecular spectrum of deuterium. They correspond to the transition $3p\pi^3\Pi_u \rightarrow 2p\sigma^3\Sigma_u^+$ and their analysis was kindly given us by Professor G. H. Dieke. The bands lie between 5939 and 6291A and were photographed in the second order of a 21-foot grating by using the usual type of discharge tube with a potential of about 4100 volts and a current of 0.75 ampere. The gas was prepared from heavy water containing more than 90 percent deuterium for which we wish to thank Professor H. C. Urey.

Density marks of known relative intensity were put on each plate by means of a tungsten filament lamp burning with constant current of 0.85 ampere and a set of eight neutral wire screens. By means of a system of slits placed directly in front of the photographic plate we were able to have a separate set of density marks for each band and thus we could correct for the change in sensitivity of the plate with wave-length. The density marks were 0.5 mm wide which corresponded to the slit-width in photographing the molecular spectrum. Under these conditions complete resolution of some of the lines was not obtained and where such was the case these lines were not used in determining the alternation of intensities.

The usual type of photographic density curves were plotted and from these the intensities of the molecular lines were determined. With the equation $\ln I/i = \ln Cg - BJ(J+1)/kT$, we have obtained values for g_s and g_a, the statistical weight due to nuclear spin for the symmetric and antisymmetric levels by a least squares solution for each branch. The measured intensity of the line is I. i is the transition probability and the other quantities have their usual significance.

The results from the Q and R branches of the (0,0), (1,1), (2,2) and (3,3) bands on two different plates gave 1.95 ± 0.06 and 2.02 ± 0.04 for the ratio g_s/g_a. Since the symmetric levels are more intense, the nucleus obeys Bose-Einstein statistics and the nuclear spin of deuterium is 1. A more detailed report will appear shortly.

G. M. Murphy
Helen Johnston

Department of Chemistry,
Columbia University,
March 24, 1934.

Transmutation of Lithium by Deutons and Its Bearing on the Mass of the Neutron

It has been recognized for some time that one of the most direct methods of obtaining the mass of the neutron is by a calculation of the mass-energy relations in the reaction

$$Li^7 + H^2 \rightarrow 2\ He^4 + n^1. \quad (1)$$

Although there is perhaps some justification for assuming that γ-rays are not involved as a product of this reaction, an experimental test has not hitherto been available. Hence, calculations of the mass of the neutron which have been made without certain knowledge as to the presence of γ-rays are to be considered strictly valid only as an upper limit.

Due to the large intensity obtainable with our apparatus, we have been able to make absorption measurements of the radiation (neutrons, plus γ-rays, if present) produced in the above reaction out to large thicknesses of both lead and paraffin, and in that way to analyze the radiation into its components for the purpose of determining whether or not γ-rays are present. It was desirable first to eliminate protons from the ion beam as far as convenient, because protons, in disintegrating lithium produce γ-rays, of the order of one quantum per disintegration, and of hardness about equal to that of the γ-rays from radium after 2 to 3 cm lead filtration.[1] This was accomplished by using rather pure (approximately 90 percent H^2 gas, and for economy it was diluted with an equal amount of helium.* It will be seen later than an effect produced by the relatively small number of protons still present appears, but can readily be identified, in the final results. During all the measurements the tube was run at 900,000 volts, with a total ion current of 5 microamperes, 3 to 4 microamperes of which it is estimated was due to deutons. The intensity of radiation obtained under these conditions was

[1] Lauritsen and Crane, Phys. Rev. **45**, 63 (1934).

* It was first made certain that helium alone produced no measurable effect.

found to correspond to the production of about 2×10^7 neutrons per second.

Curves representing the absorption of the radiation in lead and in paraffin, with both a lead and a paraffin lined ionization chamber, are shown in Fig. 1. The method of analysis is the same as we have used previously in dealing with the neutrons and γ-rays obtained from beryllium and boron bombarded with deutons.[2] The fact that all four absorption curves are nearly straight lines indicates that the radiation is almost entirely of a single kind; and further, the large displacement of the paraffin chamber curves above the lead chamber curves and the large absorption in paraffin indicate that the effect is due to neutrons. A weak component of γ-rays is indicated by the slightly greater absorption by lead for small thicknesses, as recorded by the lead lined chamber (curve IV). The dotted line represents the intensity due to neutrons alone, obtained by extrapolation, and therefore the difference between curve IV and the dotted line should be just the intensity due to the γ-ray component. The number of γ-ray quanta determined in this way is about 1/10 the number obtained in previous work under the same conditions with a beam of pure H^1, and the absorption coefficient is quite accurately the same. These γ-rays, then, are obviously to be ascribed to the protons present in the beam due to the small amount of H^1 actually contained in the heavy hydrogen used. This leaves only neutrons to be associated with the disintegration of lithium by deutons, and hence the calculations of the mass of the neutron which have been based on this process are correct, subject only to certain assumptions as to the velocity distribution of the neutrons.

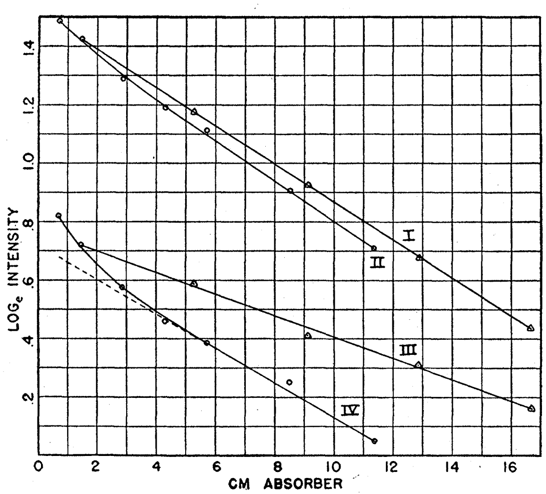

FIG. 1. Absorption of the radiation from lithium. I, paraffin lined chamber, paraffin absorber; II, paraffin lined chamber, lead absorber; III, lead lined chamber, paraffin absorber; IV, lead lined chamber, lead absorber.

If we assume that, as long as momentum is conserved, there are no restrictions on the way in which the available energy may be shared among the three particles[3, 4, 5] the two α-particles and the neutron—then it can be shown that the α-particles which come off with maximum energy would be those corresponding to the case in which the neutron happens to come off parallel to, and with the same velocity as, one of the α-particles. In this circumstance the other α-particle will, from momentum considerations, get 5/9 the total energy of the disintegration. There is no reason to doubt that this case occurs, but, since the neutron must satisfy specifications both as to direction and velocity, the probability of this occurrence must be very small. If, however, we specify simply that the energy carried away by the neutron be zero or nearly zero, then it will not be necessary to make a specification as to direction, and we will have, as the energy of the α-particle in this limiting case, just 1/2 the total energy of the disintegration. Out of a large number of disintegrations, the number which satisfy the second set of specifications will be much greater than the number which satisfy the first set of specifications, and it seems probable that under the conditions of experiment the maximum range observed may in fact correspond to the second mode of disintegration.

Oliphant, Kinsey and Rutherford[3] have made careful measurements of the ranges of the α-particles produced by bombarding lithium with deutons, and have found, as the upper limit of the continuous range, 7.8 cm, corresponding to an energy of 8.3×10^6 e.v. This group they attribute to the disintegration of Li^7, and, superimposed upon that, is a monochromatic group of greater range which is accounted for by the disintegration of Li^6. It seems entirely possible that a small number of particles due to the first mode of disintegration of Li^7 discussed above would be masked completely by the long range group from Li^6.

If we now solve Eq. (1), by using as masses of the atoms Bainbridge's values, $H^2=2.0136$, $Li^7=7.0146$, $He^4=4.0022$, and taking 0.0002 as the mass equivalent of the kinetic energy of the bombarding deutons used by the above investigators, then on the assumption that the α-particle of maximum energy observed corresponds to that mode of disintegration in which it gets half the total energy of the disintegration, we obtain for the mass of the neutron 1.0063. Essentially the same calculation can be performed in a slightly different way,[5] which perhaps involves fewer sources of error than the above, by making use of the known data on the disintegration of lithium by protons.[6, 3] By eliminating between the two equations

$$Li^7+H^2\rightarrow 2\,He^4+n^1+E_1$$
$$Li^7+H^1\rightarrow 2\,He^4+E_2$$

we obtain

$$n^1=H^2-H^1+E_2-E_1$$

in which the only atomic masses involved are those of H^1 and H^2, which are known with considerable precision. The kinetic energy of the bombarding H^1 ions and the H^2 ions

[2] Crane and Lauritsen, Phys. Rev. **45**, 226 (1934); Lauritsen and Crane, Phys. Rev. **45**, 493 (1934).

[3] Oliphant, Kinsey and Rutherford, Proc. Roy. Soc. **A141**, 722 (1933).

[4] R. M. Langer, Phys. Rev. **45**, 137 (1934).

[5] R. Ladenburg, Phys. Rev. **45**, 224 (1934).

[6] Cockroft and Walton, Proc. Roy. Soc. **A137**, 229 (1932).

used by Oliphant, Kinsey and Rutherford was, as far as we know, the same (about 0.2×10^6 e.v.), and hence cancels. The ranges of the α-particles resulting from the two reactions are nearly the same (7.8 and 8.4 cm, respectively) and since only the difference in energy is made use of, any systematic error in the measurements or in the conversion from range to energy tends to cancel out. Using $E_1=16.6\times10^6$ e.v. and $E_2=17.5\times10^6$ e.v., the difference of which is equivalent to 0.0010 mass units, we obtain for the mass of the neutron 1.0068. This we believe to be the best value on the basis of the data here discussed, and it is in agreement with the value found by Chadwick.

It is interesting, and perhaps of some significance, that γ-rays are produced in the disintegration of lithium by protons but not in the disintegration of lithium by deutons. This would lead one to suspect that the γ-ray quantum is not associated with an excitation level in the α-particle, since α-particles with high energy are produced in both instances. A solution which seems very plausible is to associate the γ-ray quantum with excited He^3 in the reaction[3]

$$Li^6+H^1\rightarrow He^4+He^3+\gamma.$$

Oliphant, Kinsey and Rutherford have observed short range particles produced in the disintegration of lithium by protons having ranges 0.65 cm and 1.15 cm. If we assume that the longer of the two ranges corresponds to He^3 and the shorter to He^4, we find that the energies† corresponding to those ranges are 1.6 and 2.1×10^6 e.v., respectively, which are just in the ratio 3 to 4, as would be expected from momentum considerations. Taking into account the γ-ray, and solving the equation for the mass of He^3, we obtain 3.0146, which is in good agreement with that to be expected from the upper branch of Aston's packing fraction curve.

It is a pleasure to acknowledge our gratitude for the support received from the Seeley W. Mudd Fund for carrying out this work.

C. C. Lauritsen
H. R. Crane

Kellogg Radiation Laboratory,
California Institute of Technology,
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† The energy of He^3 was obtained from the range-energy curve for α-particles, and corrected for the difference in mass.

The Energy Distribution of the Neutrons from Fluorine

From experiments on the ionization currents in hydrogen produced by neutrons from Be, B and F, Bonner[1] concluded that the neutrons from fluorine must have a considerably smaller average energy than those from beryllium or from boron. Curie and Joliot,[2] on the other hand, concluded that fluorine neutrons must be of high energy since they found them to be weakly absorbed by lead. Accordingly, it was desirable to make, if possible, a direct measurement of the energy of the fluorine neutrons.

It appeared that the methods of energy measurement which have been used for beryllium and boron neutrons were not especially suitable, since the intensity of the fluorine radiation is so small. It seemed entirely impractical to use recoil protons from paraffin, observed with either a counter or a cloud chamber. Indeed it seemed not feasible to observe recoil atoms with any arrangement of an ordinary cloud chamber on account of the excessively large number of photographs which would be necessary to record a reasonable number of tracks. In order to increase this number a special cloud chamber was constructed which allowed the gas pressure to be increased by a factor of more than ten. In this experiment it was used with hydrogen at a pressure of 12.9 atmospheres, so that more than a tenfold increase in sensitivity was attained. The experiment then consisted in measuring by the usual method the range of the recoil protons produced in the gas.

The source of neutrons consisted of a ten millicurie polonium source of α-particles bombarding a piece of fluorite. It was placed near the side wall of the chamber. The tracks were photographed with the usual stereoscopic camera arrangement and were reconstructed by projection.

About 9000 pairs of photographs were taken, on which 205 recoil protons were found. The ranges of these protons were measured and were then converted to air-equivalent by making use of the differential stopping-power data obtained by Gurney.[3] The number of observed recoil protons as a function of the range is shown in the curve of Fig. 1. From the curve it appears that the maximum range

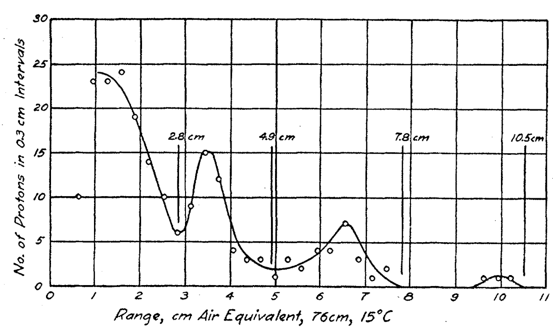

FIG. 1. Range distribution of the recoil protons from fluorine neutrons.

of the recoil protons is about 10.5 cm of air, giving the maximum energy of fluorine neutrons to be 2.5×10^6 e.v. This value is considerably less than the maximum energy of neutrons from beryllium and confirms Bonner's result.

It is seen that the curve shows distinct peaks which we believe definitely means that the neutrons are emitted with

[1] T. W. Bonner (to appear in the May 1st Physical Review).

[2] I. Curie and F. Joliot, J. de Phys. et le Rad. **4**, 278 (1933).

[3] R. W. Gurney, Proc. Roy. Soc. **A107**, 340 (1925).